June 6, 2017

Project ID # GI136

U.S. Department of Energy Vehicle Technology Office
Annual Merit Review

DOE DE-EE0006444

ePATHS - electrical PCM Assisted Thermal Heating System

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MAHLE Behr US Inc.

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ePATHS Overview

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Timeline

- Start Date – Oct. 1, 2013
- End Date – Dec. 31, 2016
  - Extended to June 30, 2017
- Percent Complete – 90%

Budget

- Total project funding: $3.5M
  - DOE share: $1.74M
  - Contractor share: $1.74M
- Funding received in BP-1: $1.1M
- Funding for BP-2: $1.2M
- Funding for BP-3: $1.2M

Note: BP-1 (4Q13 + CY2014 + Jan & Feb 2015)
BP-2 (March – December 2015)
BP-3 (January – December 2016, Extended to June 2017)

Barriers & Targets

- EV cold weather range +20%
- Phase Change Material (PCM) latent capacity +50%
- Vehicle integrated PCM heating and control system

Team/Partners

- *Ford Motor Company*
  - Vehicle reqm'ts & controls integration
- *Oak Ridge National Laboratory*
  - Simulation, design & cert. testing
- *Entropy Solutions*
  - High capacity PCM development
- *Project Lead - MAHLE*

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Relevance

Support VTP Efforts by Extending EV Range

DOE Vehicle Technologies Program (VTP)

- Reduce Petroleum usage and GHG emissions…
- Requires "…new and more fuel efficient vehicle technologies."

EV-Everywhere Grand Challenge

- "… produce electric vehicles that are as affordable for the average American family as today's gas-powered vehicles within the next 10 years (by 2022)."
- Driving range influences consumer acceptance

AOI-11 Advanced Climate Control Auxiliary Load Reduction

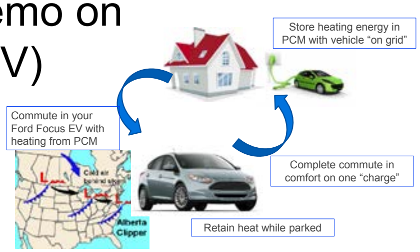
- Advanced HVAC Technologies: increase range
- "…innovative and unique heating…" using phase change materials

Extend GCEV electric range >20% by reducing or eliminating the auxiliary heating load from the vehicle battery at -10°C

- Develop "hot" PCM with >50% increase in latent heat capacity for industry application
- Develop simulation and optimization code for system and components
- Seamless vehicle integration with smart charging and discharging control
- Demonstrate performance and establish commercial viability

FY2016 Objective

- Initial vehicle build and demo on Ford Focus Electric (EV)
- Final vehicle build and demo on Ford Fusion Energi (PHEV)



Milestones
Project Execution

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Budget Period 1 –Design/Development

Milestone	Type	Description
System Component Specifications Complete	Technical	The System and component specifications will be complete
Development Level Design Complete	Go/No Go	Development Level designs for the system and components completed and ready for build.

Start 10/1/13 Finish 2/28/15

BP-1 Milestones Accomplished

Budget Period 2 – Development/Demonstrate

Milestone	Type	Description
Thermal Energy Storage Demonstration	Go/No Go	Analysis validates that the system approach results in at least 20% increase in electric drive range vs. the baseline vehicle

3/1/15 12/31/15

BP-2 Milestone Accomplished

Budget Period 3 – Integration/Validation

Milestone	Type	Description
Vehicle Integration System Complete	Technical	Integrated system testing completed and performance targets are achieved
Vehicle Testing Complete	Technical	Vehicle testing complete including evaluation of Thermal Performance, Charging Process, and Range Improvement.

1/1/16 12/31/16

BP-3 Milestone BEV Completed PHEV Extended to 6/30/2017

Approach/Strategy

General Technical Approach

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4/7/2017

6/30/2017

	Kickoff	Spec, Design	Bench and Mule	Vehicle Integra
		Budget Period I	Budget Period II	Budget Period III
		17 Months	10 Months	18 Months
Ford		• Define System Spec.	• Provide car, parts, and consult	• Vehicle validation tests
MAHLE		• Define Components Spec. • Establish system and components design • Establish control strategy and spec.	• Prototype PCM HX build and test • Insulation build • Bench and car control dev. • Bench build and test	• PCM HX Fabricatio • Vehicle control • BEV build and dem o • PHEV build and de no
ORNL+MAHLE		• Components modeling	• System modeling • Bench validation	• Car validation (Mul and Final)
Entropy+MAHLE		• PCM development strategy, candidates ident., init. dev.	• PCM development	• Complete PCM development

Background

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- Unlike a conventional vehicle, an electric vehicle (EV) does not have excess thermal energy (“waste heat”) available from the engine to heat the cabin
- Must be heated using an on-vehicle energy source
- When cabin heating is provided by the main battery, the power required can significantly penalize the driving range in very cold environments (30-60% typical!)
- Results in lower consumer acceptance of EVs:
  - Additional battery capacity required to meet range requirements ($$$)
  - Reduced range in winter months not acceptable for some drivers

Image courtesy of Ford

ePATHS Technical Objectives

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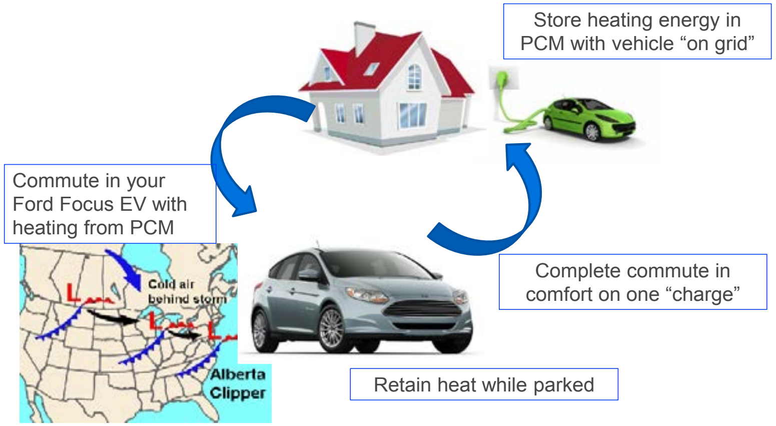
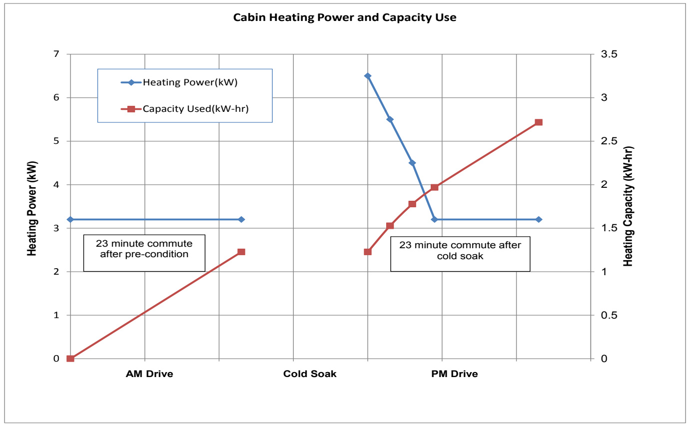
Extend BEV electric range >20% by reducing or eliminating the auxiliary heating load from the vehicle battery at -10ºC

- 90 percentile of commute trips in US
- Develop “hot” PCM with >50% increase in latent heat capacity for industry application
- Develop simulation and optimization code for system and components
- Seamless vehicle integration with smart charging and discharging control
- Demonstrate performance and establish commercial viability

Typical Commute Usage Cycle



Representative Heating Demand



ePATHS Overall Architecture

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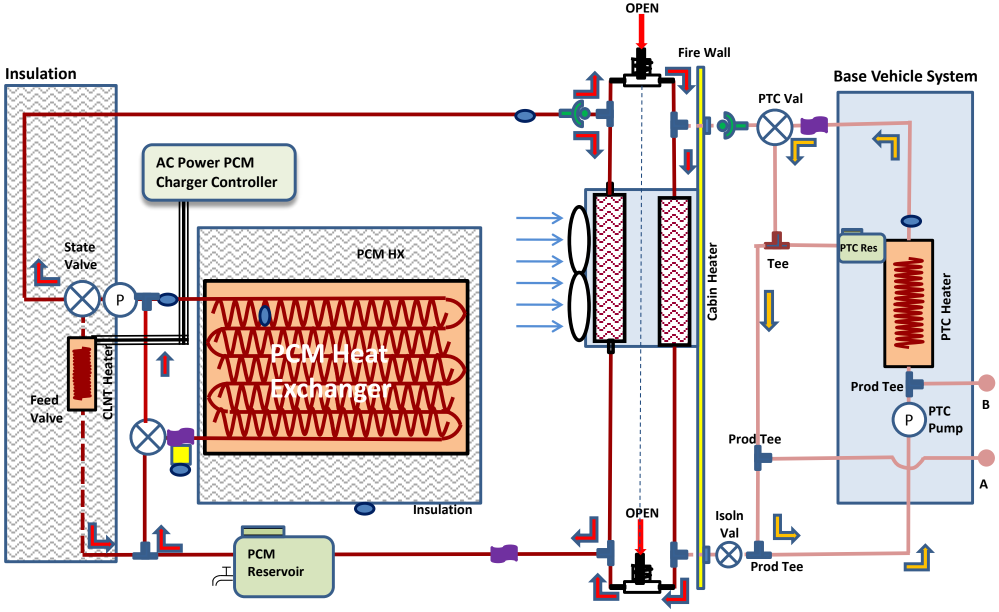
System architecture designed to accommodate 4 modes of operation:

- PCM Charging
- PCM Heating
- PCM Preheating
- PTC Heating

Image courtesy of Ford



PCM Heat Exchanger Design and Development

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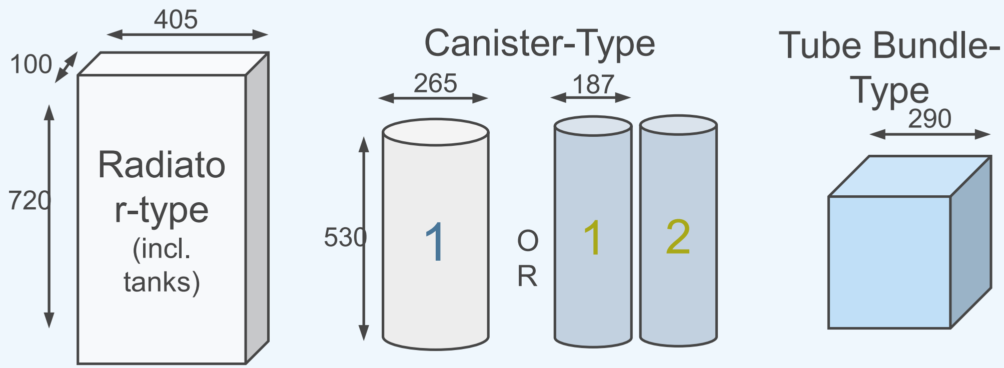
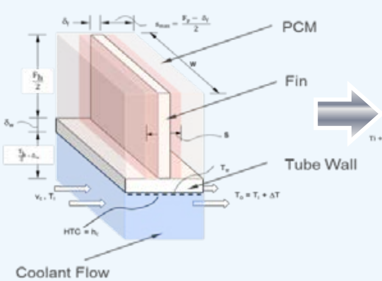
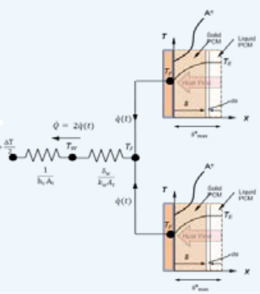
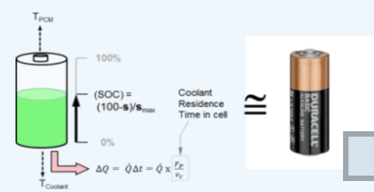




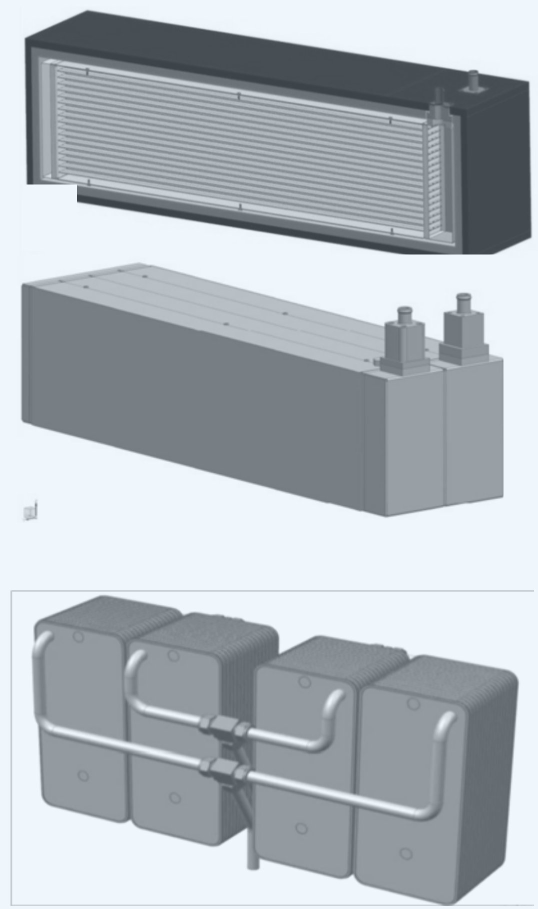
Thermal Unit



Simplified Thermal Resistance Model



Equivalent Thermal Battery Cell



Technical Accomplishments and Progress

Electrical Architecture and Control

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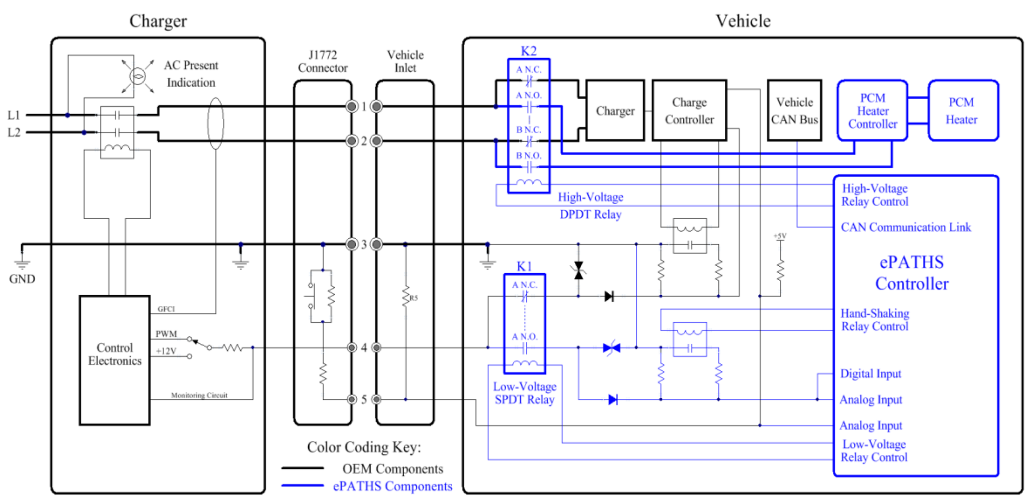
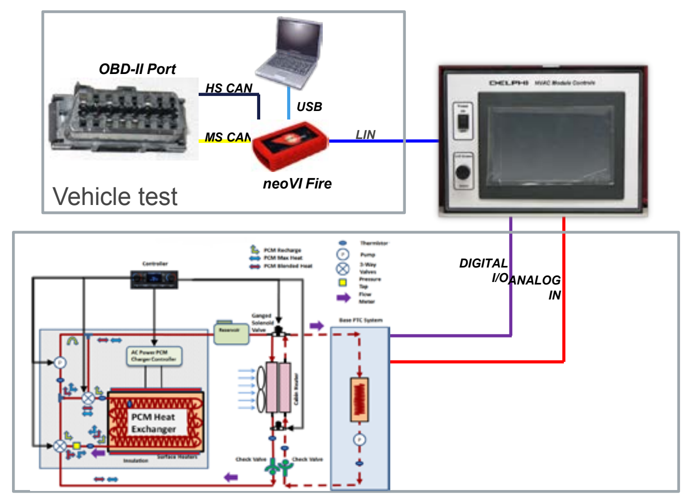
- Custom system controller for manual and automatic operations of ePATHS system
  - Communicates with vehicle bus for vehicle state and control targets
  - Manages operating mode switching
  - Manages PCM heat discharge according to vehicle targets
- Custom designed electrical system to share battery charger
  - Controller monitors traction battery charging status
  - Once traction battery is fully charged, ePATHS charging begins





Phase Change Materials Development

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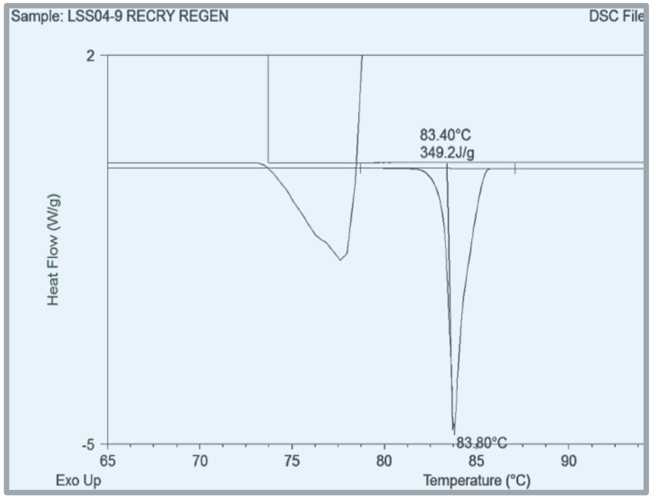
- **PCM development objective**
  - ✓ Synthesis of PCMs that undergo phase change near 85 ºC (vs. 90–100 ºC)
  - ✓ PCM with high latent heat (350 J/g)
- **Products**
  - ✓ 2 PCM materials have been developed
  - ✓ DPT68: Phase change temperature 68 ºC, latent heat ≥340 J/g
  - ✓ DPT83: Phase change temperature 83 ºC, latent heat ≥340 J/g
- **PCM-aluminum compatibility**
  - ✓ Al 3003 coupons exhibiting negligible corrosion rate
  - ✓ Coupon Mass Loss Comparison: virgin Al3003 < with Dry Flux < with Glycol Flux
  - ✓ Dry Flux powder has limited solubility in DPT68
- **PCM commercialization study**
  - ✓ Outside Contract Manufacturing not a viable option
  - ✓ Designated Plant Construction
    - » At 1 million kilogram per year volume, pricing will be viable
    - » Initial investment needed for plant construction

PureTemp



Vacuum Insulation Panel (VIP) Development

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- **Scope of VIP development**
  - ✓ Develop specification requirements
    - » VIP meeting 10% heat loss over 8 hours under -10 ºC ambient, with PCM temperature between phase change temperature and 120 ºC
  - ✓ Identify supplier/vendor for prototype VIP container for PCM thermal storage heat exchanger
  - ✓ VIP for heat loss evaluation on bench and in vehicle
- **VIP development findings**
  - ✓ VIP meeting 8% heat loss over 8 hours under -10 ºC identified and tested
  - ✓ Thermal conductivity: λ = 3.5 mW/(m·K)
  - ✓ Current technology state sufficient to support commercial applications

Predicted VIP Performance (with Thickness and in Time)

Initial Thermal Conductivity [mW/(m.K)]	24Hr Energy Target (%)	VIP Thickness (mm)	10Yr Thermal Conductivity [mW/(m.K)]
3.5	70	10	6.2
3.5	80	16	5.3
3.5	90	36	N/A

PCM Heating System Bench Build and Testing

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Bench Test Objectives

- Demonstrate control system functionality
- Perform PCM HX charging, discharging operations
- Evaluate charging/discharge rate for heating applications
- Evaluate heat storage capacity
- Evaluate thermal insulation effectiveness
- Evaluate vehicle range impact

Approach

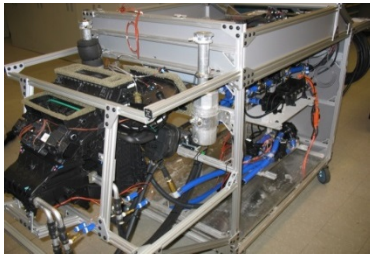
- Initial build, debugging and testing at MAHLE, Lockport, NY
- Validation testing at ORNL

Basic Test Procedures

- Charge to 120ºC
- Discharge PCM HX heat to HVAC module to deliver required air discharge temperature and flow rate (12 ltr/min). Test chamber set at -10 ºC
- Soak under -10ºC for 8 hours to evaluate heat loss.

Test Results

- **Projected Focus BEV base range extension:10.3~14.1 miles, percentage range extension: 21~28%**
- **Projected Focus BEV total range extension with energy recovery: 15.6~17.3 miles, percentage range extension:31~34%**



Cases	Units	Energy_120	Energy_60	Energy_25	Heat_120~60	Heat_25~60	Total
Projection with h=340 j/g	MJ	15.8	6.4	3.2	9.5	3.2	12.7
	kWh	4.40	1.77	0.88	**2.64**	**0.88**	**3.52**
Surface Heater	MJ	15.0	6.9	2.8	8.1	4.1	12.2
	kWh	4.17	1.93	0.78	**2.24**	**1.15**	**3.39**

Vehicle Build and Testing

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Test Protocol

- -10 ºC Cold Soak for 3 hours
- Protocol 1: 50 kph constant speed driving till full traction battery discharge
- Protocol 2: Repeated UDDS cycles driving till full battery discharge
- Tests are repeated for HVAC ON and OFF for range comparison

Test Summary

- At -10 ºC, PTC cabin heating reduces range between 40~50%
- Using PCM thermal storage for cabin heating and supplemented by PTC, vehicle range is extended by 26%

Range Impact of PTC Heating at -10 ºC

Test	Decrease in Range
Constant 50kph	40%
UDDS Cycle	47%

Range Extension by PCM Heating

	With PTC	With ePATHS	Range Change
Range	68km	85.7km	+26%

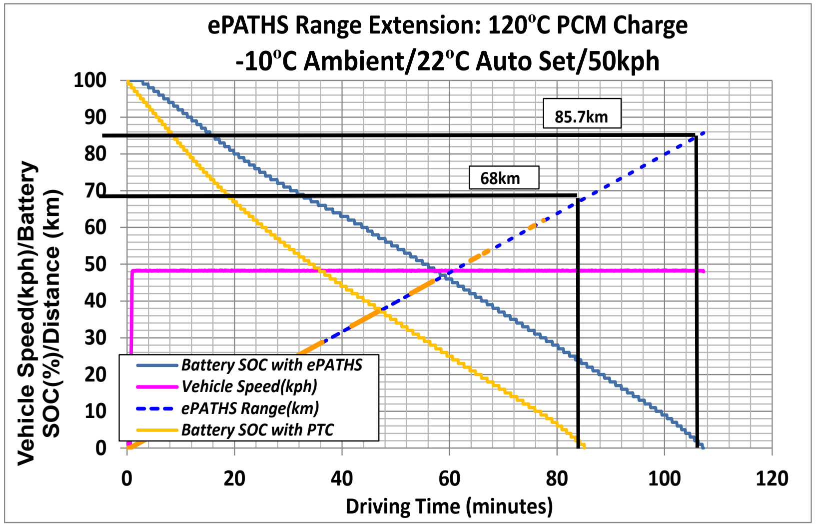
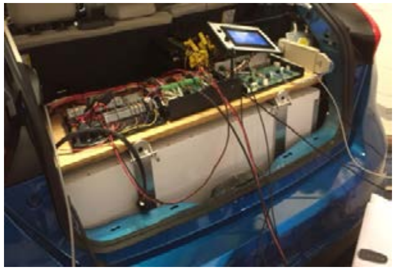
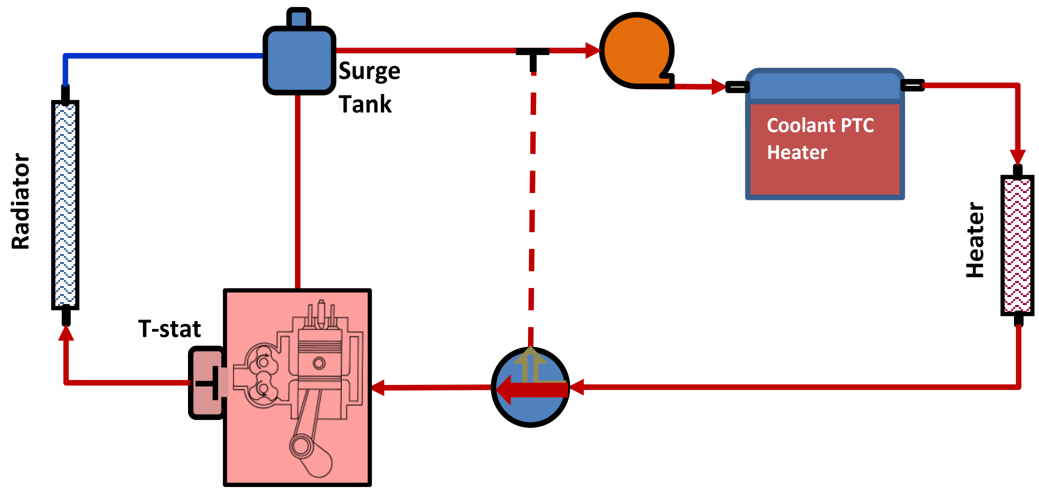


Image courtesy of Ford



Application to Plug-In Hybrid Electric Vehicle

- Typical PHEV has PTC heater and engine as heat sources
- With battery charged, preferred heating mode is using PTC heater
- Engine starts when traction battery is discharged
- Engine also starts when ambient temperature is colder than a critical temperature (-5 ºC , e.g.) to provide cabin heating regardless of traction battery state.



PHEV Cabin Heating System Design Characteristics with PCM Heating

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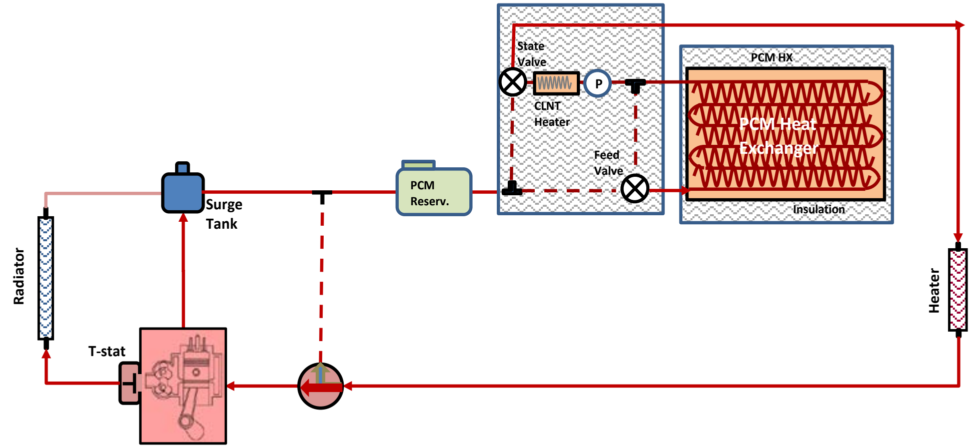
- ePATHS system directly replaces PTC heater and pump
- PCM thermal storage may be flexibly sized
  - ✓ Based on average driving profile
  - ✓ Or, based on battery capacity
- Four operating modes can be achieved
- Transition between ePATHS and engine needs to be planned for stable comfort
- No low grade heat recovery from PCM thermal storage is necessary once engine starts
- Low grade heat from thermal storage may be used to preheat engine for emission reduction

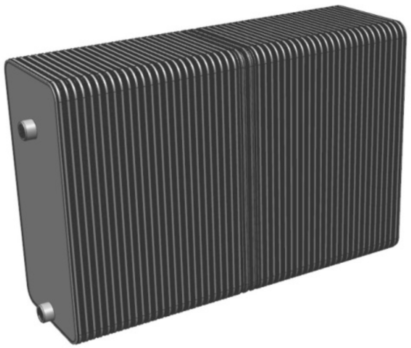
ePATHS Operating Modes

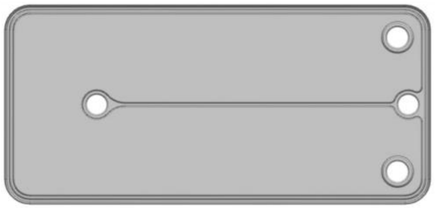
Mode	Feed Valve	State Valve	Engine Valve	PCM Clnt Heater	PCM Pump
Engine Heating	0%	Discharge	Left	OFF	ON
PCM Heating	0%~100%	Discharge	Up	OFF	ON
PCM Charging	100%	Charge	Up	ON (XX%)	ON
PCM Pre-Cond.	0%	Discharge	Up	ON (XX%)	ON

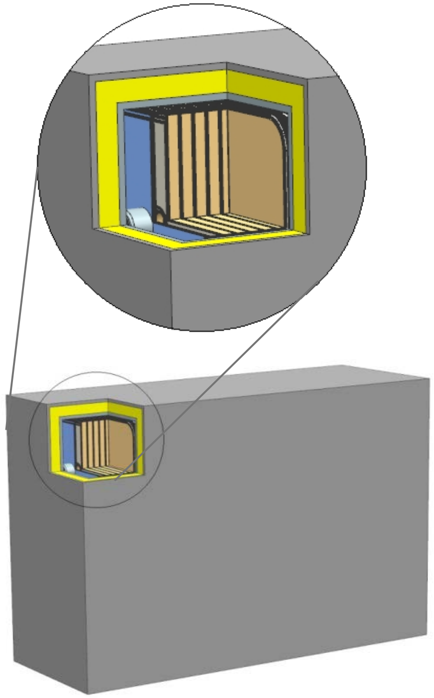


New Features of PCM Thermal Storage Design for PHEV

- Plate type PCM heat exchanger has uni-body design (vs. modular design) for compact packaging
- Total dimension is 635x245x290mm
- 15mm VIP insulation container
- DPT83 is used
  - Phase change temperature meets standard coolant temperature specification for PHEV
  - Sustains independent heating without need for supplemental PTC heating







Technical Accomplishments and Progress

PCM Heat Exchanger Validations

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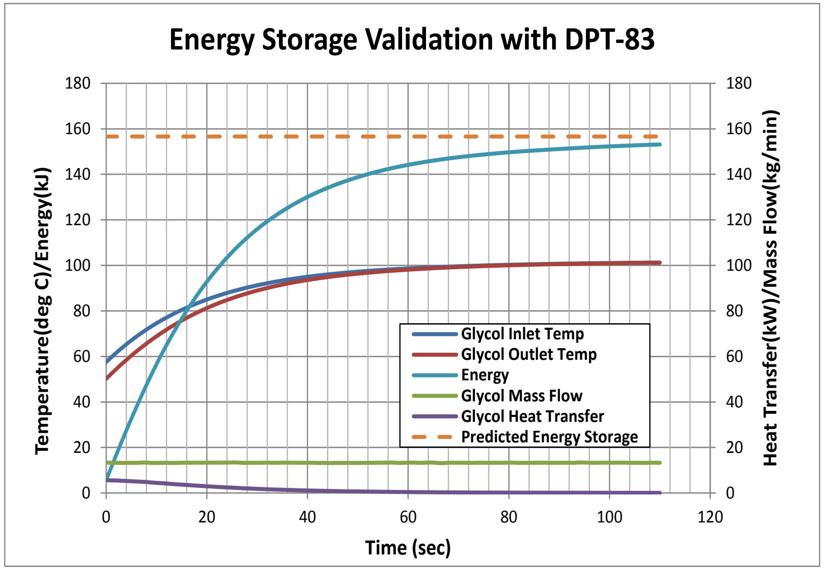
- **Multiple units bursted for coolant side and PCM side pressure limit testing**
- **Pressure cycling tests ongoing**
- **Thermal cycling tests ongoing**
- **PCM latent heat validation completed using small HX**

	Pressure (PSI)	Pressure (MPa)
PCM Side Burst Pressure	239	1.65
Coolant Side Pressure	286	1.97



Working Together!

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- **MAHLE Is Lead Organization**
  - Significant automotive experience. HVAC system, compressor, heat exchanger development expertise and global manufacturing footprints
  - Responsible for system and components design, development and vehicle integration
- **Strong Sub-Recipient Teams**
  - Ford – OEM who produces GCEV
  - ORNL – Modeling and analysis in transportation technologies
  - Entropy – Leading PCM technology and material supplier
- **Weekly Project Execution Meetings**
  - Focus on task execution and timing
  - Resolve technical and resource issues
  - Communication
- **Face to Face Technical Meetings**
  - Regular site visits and as-needed technical meetings

Future Work

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- Integration of ePATHS system into Ford Fusion PHEV
- Evaluate Fusion PHEV range impact of ePATHS system

Any future work is subject to change based on funding levels.

Work plan:

	2016										2017						
Month	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	
Focus Build & Test					Complete												
	Spec. Update and build new components								Complete					Fusion Build & Test			Car to DOE

Response to Previous Year Reviewers' Comments

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Comments from 2016 AMR	Response
Reviewer #1: The reviewer asked what the vehicle mass and packaging volume tradeoffs are for this application and how these will affect commercial feasibility. Reviewer #2: … yet, the PCM packaging issue is a bit of a setback because it limits practical application of the technology.	Packaging issues should be addressed in three ways: 1. "Right sizing" of the PCM thermal storage based on driving profile analysis 2. Improving PCM thermal storage packaging design by optimizing between "modular" and "uni-body" 3. Packaging design of PCM thermal storage at the same time as traction battery
Reviewer #2: … The reviewer proposed that the overall energy efficiency of the system from a wall-to-wheels perspective should be reported. Reviewer #3: … The project team indicated that the grid-to-wheels efficiency of the system is better than using the battery to run the positive temperature coefficient heater. This should be quantified and communicated.	This can be understood from the following facts: 1. Battery charging efficiency at ~95%; PTC heat conversion at 100%; Parking loss unknown 2. PCM charging efficiency at 100%; Parking loss at less than 10% 3. Wall-to-wheel efficiency about the same

Summary and Conclusions

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- BEV PCM Heating Demonstration
  - Demonstration of cabin heating with PCM thermal storage on BEV has been completed
  - 26% range extension achieved on Ford Focus Electric at -10 °C, exceeding 20% target commitment
  - PCM thermal storage provides a balanced approach to break BEV's range design conundrum:
    - ✓ Design for winter at unmanageable cost, or
    - ✓ Design for summer but face winter range reduction
  - Proper design point for PCM thermal storage capacity needs to be carefully considered based on driving profile analysis
  - Packaging needs to be managed early during design process
- PHEV Demonstration
  - System integration design with PHEV has been completed
  - DPT83 PCM will be used as thermal storage medium
  - Compact PCM heat exchanger design and fabrication completed
    - ✓ Product validation partially completed
  - Upcoming work:
    - ✓ Complete vehicle build
    - ✓ Validate control system
    - ✓ Climate tunnel testing

Acknowledgement

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Thank you for your attention!

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